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DOI: https://doi.org/10.1080/00365520600610451

Originally published at:
Steingoetter, Andreas; Fox, Mark; Treier, Reto; Weishaupt, Dominik; Marincek, Borut; Boesiger, Peter; Fried, Michael; Schwizer, Werner (2006). Effects of posture on the physiology of gastric emptying: a magnetic resonance imaging study. Scandinavian Journal of Gastroenterology, 41(10):1155-1164.
DOI: https://doi.org/10.1080/00365520600610451

Scandinavian Journal of Gastroenterology, 2006; 41: 1155–1164

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ORIGINAL ARTICLE

Effects of posture on the physiology of gastric emptying: A magnetic resonance imaging study

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Abstract

Objective. Gastric contents empty from the stomach despite frequent changes in body position. The mechanism that maintains gastric emptying independent of position is poorly understood. The aim of this study was to determine the effects of body position on gastric emptying and motor function. ***Material and methods***. Twelve volunteers were investigated in seated position (SP) and upside-down position (UDP) after ingestion of 300 ml water. Magnetic resonance imaging provided a non-invasive assessment of gastric emptying and volumes, intragastric distribution and peristaltic function. ***Results***. A marked difference in distal/proximal intragastric distribution between UDP and SP was present (7% versus 40%; $p < 0.01$). Gastric-emptying time was similar but emptying pattern was linear in UDP and exponential in SP. Peristalsis was slower in UDP than SP (2.75 versus 2.96 min^{-1}; $p < 0.01$), but no correlation was found between peristaltic frequency and the rate of gastric emptying in either position. Postprandial volume response (gastric relaxation) was greater in UDP than SP (280 versus 250 ml; $p < 0.05$). A correlation was found between gastric relaxation and gastric-emptying time in SP ($r^2 = 0.46$) but not in UDP. ***Conclusions***. The stomach maintains the rate of gastric emptying despite radical changes in body position and intragastric distribution of gastric contents. In SP, hydrostatic pressure (modulated by gastric tone) dictates the gastric emptying. In UDP, gastric emptying also appears to be mediated by continuous adaptation of gastric tone. These findings provide support for the hypothesis that the mechanism of gastric emptying resembles a "pressure pump" rather than a "peristaltic pump".

Key Words: *Gastric emptying, gastric motor function, intragastric air, intragastric distribution, magnetic resonance imaging, posture*

Introduction

After a liquid meal gastric contents usually empty from the stomach at a steady rate, maintaining the delivery of fluid and nutrients to the absorptive surface of the small bowel [1]. To be effective, this process must continue despite major changes in body position. The effect of position on the rate and physiology of gastric emptying has been extensively investigated over the past 40 years using various test meal measurement techniques [2–9]. Different methodologies produced conflicting results and hence several aspects of this complex homeostatic mechanism remain controversial.

The first law of thermodynamics (conservation of energy) demands that the movement of liquid (kinetic energy) requires a driving force (i.e. potential energy). For gastric emptying, this potential energy could be produced either by a continuous, small pressure difference between stomach and duodenum, or intermittent, propagating high-pressure waves. Based upon these physical principles and to be consistent with previous data [10], we called

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(Received 14 July 2005; accepted 31 January 2006)

ISSN 0036-5521 print/ISSN 1502-7708 online
DOI: 10.1080/00365520600610451

these two mechanisms the "pressure pump" and "peristaltic pump". This study was designed to investigate which of these mechanisms drives gastric emptying, and whether the dynamics and physiology of gastric emptying are affected by a change of position.

Studies using antroduodenal manometry and concurrent duplex ultrasonography [11,12] or magnetic resonance imaging (MRI) [10] have suggested that the "pressure-pump" mechanism is important in the gastric emptying of fluids.

The "pressure pump" model does not imply that high pressure drives gastric emptying; rather the process is more a function of volume displacement, where the stomach adapts its tone (as reflected by changes in gastric volume and shape) to move contents from the proximal to the distal stomach and through the pylorus without the generation of high pressure or pressure gradients.

However, these studies were all performed in the upright sitting or right-lateral positions with the antrum and duodenum in a dependent position in which the antroduodenal pressure gradient (and buoyancy) is conducive to transpyloric outflow. Thus this research could not clarify the relative importance of the "pressure-pump" and the "peristaltic-pump" during position change.

Gastric MRI provides unique advantages for the non-invasive, simultaneous assessment of gastric emptying and gastric motor function. Studies using this technique have validated the measurement of gastric accommodation, peristaltic activity, intragastric distribution and gastric emptying [13–23]. MRI appears to have many characteristics of an "ideal" method for investigation of gastrointestinal function [24] and provides a detailed and quantitative assessment of gastrointestinal structure and function. The aim of the current study was to apply gastric MRI to the study of posture on the rate and physiology of gastric emptying. A non-nutrient liquid (water) was used in order to preclude possible confounding by feedback inhibition from intestinal chemoreceptors. An open-configuration MRI system allowed the non-invasive measurement of gastric physiology in the upright, seated and upside-down position for the first time. Radically different positions were chosen to provide the clearest possible demonstration of whether different mechanisms of gastric emptying were operating. We hypothesized that the upright, seated position (SP) would increase the gastroduodenal hydrostatic pressure gradient and favor the "pressure-pump" mechanism, whereas the upside-down position (UDP) would require the "peristaltic-pump" to force the liquid against the pressure gradient and through the empty antrum into the duodenum.

Material and methods

The measurement protocol was approved by the local Institutional Review Board and the ethics committee of the University Hospital. Informed consent was obtained from all volunteers who participated in this study.

MRI measurements

Twelve healthy volunteers of normal weight (10 M, 2 F, age 24–34 years, body mass index (BMI) 20.1–26.1 kg/m^2) were investigated in an open-configuration MRI system (Sigma SP/i 0.5 T; GE Medical Systems, Milwaukee, Wis., USA). The special architecture of this MRI system with a 56-cm-wide gap between two vertically placed ring magnet components allows imaging of volunteers in arbitrary body position. The investigations were performed consecutively, first in the upright SP and then in the UDP on the same study day (Figure 1a). In the UDP, subjects rested on their shoulders while being supported from behind (Figure 1b). In this posture, the long axis of the stomach was always at an angle steeper then 45° to the horizontal scanner table and the antrum was essentially filled with air (Figure 2a, b (lower panel)). The volunteers ingested 300 ml water labeled with 0.5 mM Gd-DOTA (DOTAREM®, Laboratoire Guerbet, France) in the corresponding body position within 1 min using a sports bottle to minimize spillage and air swallowing. Before and immediately after water intake, an MRI "volume scan" covering the complete gastric region (details below) was acquired (Figure 2a). Further volume scans, each followed by dynamic "motility scan" sequences (details below), were performed every 5 min for up to 30 min. For the motility scans, one oblique coronal image plane was aligned with the long axis of the stomach such that the antrum always lay in this plane. In this way, the propagating gastric contraction waves could be followed over time (Figure 2b). After gastric emptying in SP was complete, the UDP was assumed and the process was repeated.

A fast spoiled gradient echo (FSPGR) sequence and a standard abdominal surface coil were applied for image acquisition. For the volume scan: 20 sagittal image slices, Tscan = 44 s (during 2 breath-holds), TR/TE = 17/8 ms, flip angle = 60°, $\Delta z = 10$ mm, matrix 256 × 160, FOV = 350 mm, RFOV = 0.75. For the motility scan: 50–70 dynamics, oblique coronal image slice, Tscan = 79–148 s (during gentle breathing), TR/TE = 17/8 ms or 13/6 ms, flip angle = 60°, $\Delta z = 10$ mm, matrix 256 × 160, FOV = 350 mm, RFOV = 0.75) with images recorded every 1.6 to 2.1 s.

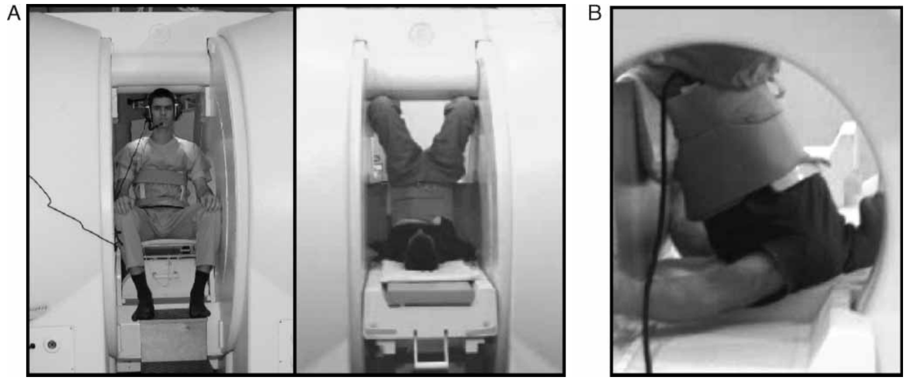

Figure 1. a. The 0.5 T open configuration MRI system with a volunteer in seated position (SP) (*left*) and upside-down position (UDP) (*right*). b. In UDP the long axis of the stomach was always at an angle steeper then 45° to the horizontal scanner table. The standard abdominal surface coil was fixed around the subject's abdomen.

Data analysis

Fasting and postprandial total stomach volume and meal volume (labeled water) were outlined for each volume scan using a semi-automatic segmentation method. Gastric air made up the difference between total stomach and meal volume. In addition, the stomach was divided into proximal and distal compartments based on the 3-dimensional plot of the stomach contours (Figure 3a). Total, proximal and distal stomach volumes, meal volumes and gastric air volumes were plotted over time to generate "volume curves". The primary outcome measures were fasting and initial postprandial gastric volumes, gastric relaxation, gastric-emptying half-time of the meal in SP and UDP and an assessment of intragastric water distribution between the proximal and distal stomach over time. Secondary analyses included measurement of gastric peristalsis and changes in total postprandial stomach and gastric air volume. Changes in total stomach volume provide an indirect assessment of relative change in gastric tone. Gastric air volume was analyzed because it contributes to stomach volume and may affect intragastric pressure and gastric tone (and thus gastric emptying).

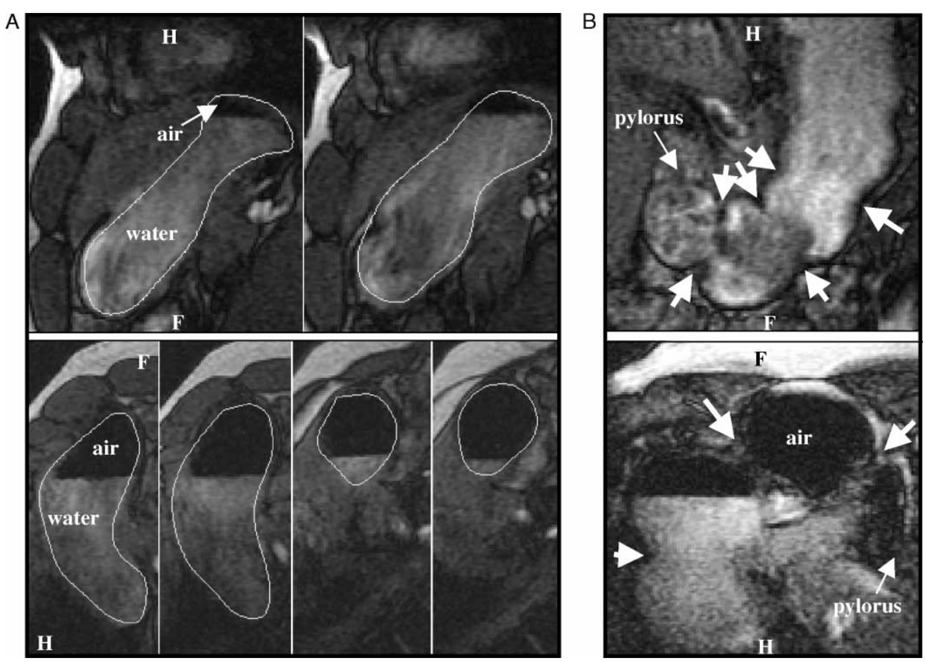

Figure 2. a. Consecutive sagittal images of MRI volume scans from a volunteer in seated position (SP) (*upper panel*) and upside-down position (UDP) (*lower panel*), respectively. Stomach contours are outlined in each image. The images demonstrate the prominent difference in intragastric meal (water) and air distribution (F: feet direction, H: head direction). b. Oblique coronal images of motility scan from the same volunteer in SP (*upper panel*) and UDP (*lower panel*). Peristaltic contraction waves (*white arrows*) and the position of the pylorus are indicated in the images. The UDP motility image nicely depicts that gastric air was confined to the distal stomach in this position (F: feet direction, H: head direction).

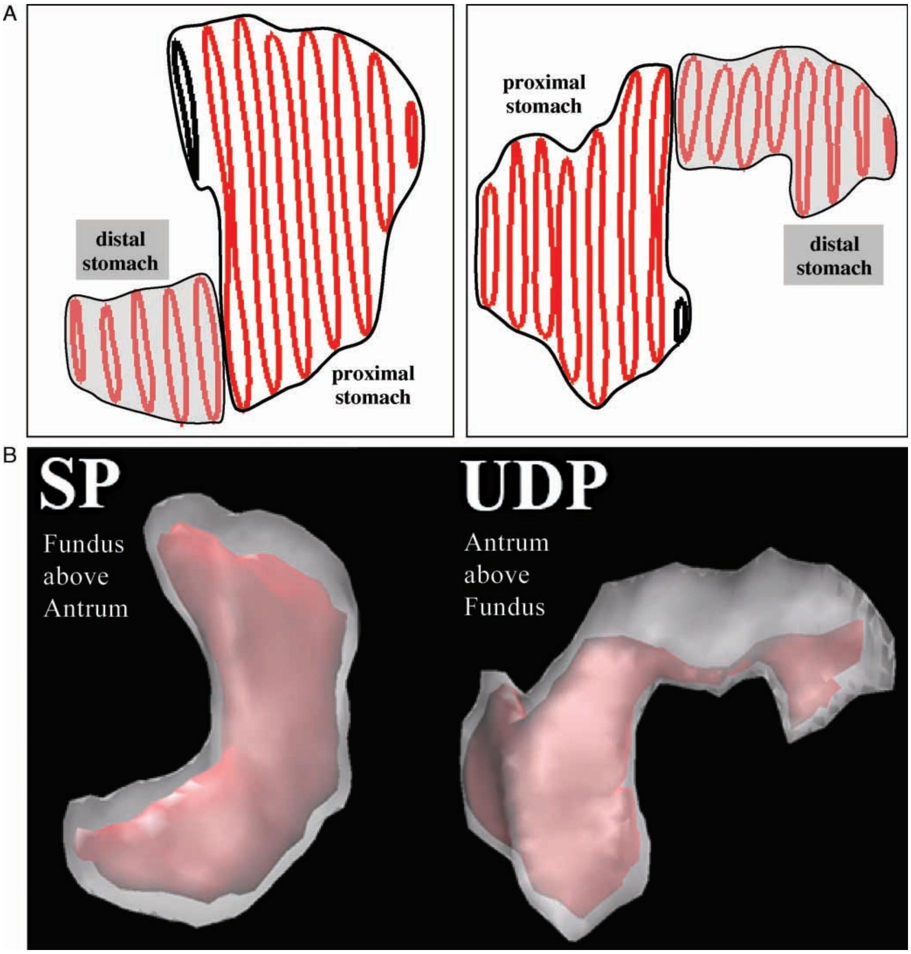

Figure 3. a. 3D contour plot of initial postprandial stomach volume of a volunteer in seated position (SP) (*left*) and upside-down position (UDP) (*right*). The division into proximal and distal stomach volume is indicated. b. Corresponding 3D visualizations of initial stomach (*white*) and meal (*red*) volumes. The meal volumes (*red*) were down-scaled to prevent overlapping of rendered surfaces. The 3D representation was performed to provide qualitative information on intragastric distribution and stomach shape.

Gastric relaxation was defined as the volume difference between the initial postprandial ($t = 0$ min) and fasting ($t = -2$ min) stomach volume. Gastric emptying was defined as the change in meal volume over time. The relative intragastric distribution was defined as the ratio of distal to proximal water volume, in percentage. By convention, volume measurements were normalized to the volume immediately after meal ingestion and expressed as a percentage. This transformation reduces inter-individual variation and facilitates statistical comparison. The normalized gastric-emptying data were plotted for each subject and gastric-emptying halftime ($t_{1/2}$) was calculated for total meal emptying. For both positions, a linear and exponential regression was fitted to the gastric-emptying data. The coefficients of the linear (r^2lin) and exponential (r^2exp) fit were calculated. In addition, the generated volume curves were statistically compared to analyze the effect of body position and time on the total stomach, meal and gastric air volume.

Peristalsis (phasic motility) was assessed as the average frequency of all detected propagating contraction waves in a volunteer, now referred to as peristaltic activity. In addition, the average frequency within each 5-min interval was plotted over time [15,20] to generate a "frequency curve".

Statistics

Data were not normally distributed and were expressed as the median (interquartile range). By convention, in the figures the data are presented as mean values ($\pm$SD). In four subjects, measurements could not be performed at time $t = 30$ min. The last observation carried forward (LOCF) approach was used to fill in the missing data points. The primary outcome measurements as well as peristaltic activity from SP and UDP were statistically compared using the Wilcoxon matched pairs test. A two-way (body position and time) repeated measures ANOVA with Greenhouse-Geisser correction was used to analysis the volume curves and determine the influence of body position and time on the peristaltic frequency and the stomach, meal and gastric air volumes (secondary outcome measures). Analyzing the interaction between body position and time allows assessment of differences in the characteristics (dynamics) of the volume curves between the two positions. A p-value of <0.05 was considered to be significant.

Results

Image acquisition and analysis was successful in all subjects. Fasting and postprandial stomach volumes and meal volumes were detected and outlined in SP and UDP and 3-dimensional (3D) visualization of the stomach was performed (Figure 3b).

Fasting and initial postprandial volumes

Gastric volumes in the fasting and initial postprandial condition as well as gastric relaxation and the difference between fasting and initial postprandial gastric air volume are listed in Table I. Although there was no difference in fasting stomach volume and meal volume, i.e. residual gastric contents, between the two positions, fasting gastric air volume was slightly larger for SP. After water ingestion, meal volume was similar, but initial total stomach volume showed a trend towards a larger volume in UDP. This difference was due to a pronounced difference in initial gastric air volume. Gastric relaxation, as well as the difference between fasting and initial postprandial gastric air volume, was greater for UDP. In both positions, stomach volume was greatest immediately after meal ingestion. For SP, the correlation between initial postprandial stomach volume and gastric-emptying halftime was ($r^2 = 0.47$). No correlation was found for UDP.

Intragastric distribution

A marked difference in intragastric distribution was present between SP and UDP after meal ingestion. In UDP, the ratio of distal to proximal meal volume remained constant at around 8% (6–9%) highlighting that almost all ingested fluid was retained in the proximal stomach. In SP, this ratio was consistently higher than in UDP ($p < 0.01$) and increased over the study period from 23% (19–32%) at t = 0 min to 58% (26–100%) at t = 30 min due to relatively greater emptying from the proximal stomach than from the distal stomach.

Gastric emptying

Normalized gastric-emptying data in SP and UDP are delineated in Figure 4a. Measurement error is very low for MRI assessments of gastric volumes [25]; however, there was a large inter-individual variation for the water emptying as denoted by the large standard deviations. No lag phase was observed and total stomach volume decreased with meal volume until emptying was complete. No significant difference was detected for the gastric-emptying half time ($t_{1/2}$: SP: 15.8 min (11.5–17.0 min) versus UDP: 18.3 min (13.8–19.3 min); $P = 0.07$), and emptying was completed within 25 min in both positions. In SP the regression that provided the best fit to the normalized gastric-emptying data was exponential. In UDP the best fit was linear (r^2 lin $= 0.96$ (0.95–0.98) versus r^2 exp $= 0.92$ (0.9 – 0.96); $p < 0.05$). As shown in Figure 4b, this difference was even more clearly demonstrated when the pattern of gastric emptying from the proximal and distal stomach was considered ($p <$ 0.01 for all comparisons). In SP, water was retained in both the proximal and distal stomach; the meal emptied in an exponential fashion from the proximal and distal stomach (Figure 4b, left). In UDP, almost all the water was retained in the proximal stomach

Table I. Stomach volume, meal volume and intragastric air volume in the fasted condition and after ingestion of 300 ml water in SP and UDP. Gastric relaxation and the difference between fasted and initial postprandial air volume after ingestion for SP and UDP.

	SP		UDP	
	Fasted	After water	Fasted	After water
SV (ml)	122 (103–149)	377 (345–401)†	101 (81–142)	417 (359–458)†
MV (ml)	28 (18–54)	296 (279–323)	40 (0–75)	290 258–323)
AV (ml)	89 (62–113)*	64 (53–93)‡	75 (51–82)*	123 (80–140)‡
GR (ml)		250 (219–271)*		280 (255–338)*
AD (ml)		−16 (−44–10)‡		58 (31–82)‡

Abbreviations: SV = stomach volume; MV = meal volume; AV = intragastric air volume; SP = seated position; UDP = upside-down position; GR = gastric relaxation; AD = postprandial air volume.

*Significant difference with $p < 0.05$ between SP and UDP; †trend for a difference with $p = 0.06$ between SP and UDP; ‡significant difference with $p < 0.01$ between SP and UDP.

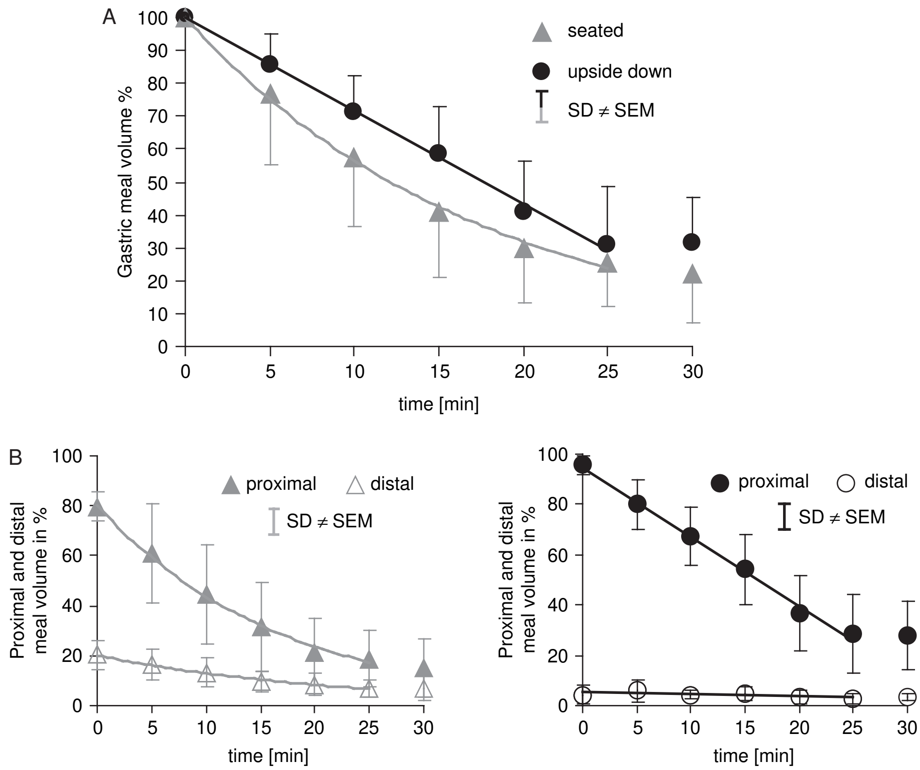

Figure 4. a. Gastric-emptying curves for seated position (SP) and upside-down position (UDP). The regression was fitted to the first 25 min because negligible emptying occurred after this time (i.e. a small gastric residual was present). Measurement error of gastric volumes is low. The standard deviations provided reflect the large inter-individual variation in gastric emptying. b. Proximal and distal meal volumes over the 30-min study period (expressed as a percentage of the total meal volume) in SP (*left*) and UDP (*right*). In SP, water was retained in both the proximal and distal stomach and emptied from both compartments in an exponential fashion. In UP, almost all the water was retained in the proximal stomach with only a minimal amount seen in the distal stomach. The meal emptied in a linear fashion from the proximal stomach, whereas the (small) volume in the distal stomach remained constant.

with only a minimal amount seen in the distal stomach; gastric contents emptied in a linear fashion from the proximal stomach, whereas the (small) volume in the distal stomach remained constant (Figure 4b, right). These findings are reflected in the statistical analysis comparing the total, proximal and distal meal volume curves for SP and UDP. The analysis of the *total* volume curves showed a significant effect of time (decrease in both meal volumes) ($F_{tot}(2,23) = 184$, $p < 0.001$), a non-significant effect of body position (similar meal volumes) and a strong trend for a significant interaction between body position and time (trend for different dynamics of the volume curves) for the first 20 min of the study period ($F_{tot}(3,29) = 2.9$, $p = 0.059$). The analysis of the *proximal* volume curves showed a significant effect of time ($F_{prox}(2,22) = 177$, $p < 0.001$), a significant effect of body position ($F_{prox}(1,11) = 5.8$, $p < 0.05$) and a non-significant interaction between body position and time for the complete study period. The analysis of the *distal* volume curves showed a significant effect of time ($F_{dist}(3,33) = 33.8$, $p < 0.001$), a significant effect of body position ($F_{dist}(1,11) = 28.8$, $p < 0.001$) and a significant interaction between body position and time ($F_{dist}(3,28) = 18.2$, $p < 0.001$) for the complete study period.

Gastric peristalsis

Peristalsis was observed in all subjects in both positions. The degree of occlusion increased as the peristaltic wave progressed along the long axis of the stomach and complete occlusion was present in the distal antrum (Figure 2b). Peristaltic activity was different for SP and UDP, with a higher average frequency of propagating contraction waves in SP (SP: 2.96 1/min (2.83–3.06) versus UDP: 2.75 1/min (2.59–2.90); $p < 0.01$). Peristaltic frequency (higher in SP) increased after the first 5-min interval and then remained constant until gastric emptying was complete ($p < 0.01$) (Figure 5b, right). These findings again are reflected in the statistical analysis comparing the frequency curves for SP and UDP. There was a significant effect of time (initial frequency increase) ($F_{freq}(3,30) = 12.4$, $p < 0.001$), a significant effect of body position (higher frequency for SP) ($F_{freq}(1,11) = 23.4$, $p < 0.05$), with no significant interaction between body position and time

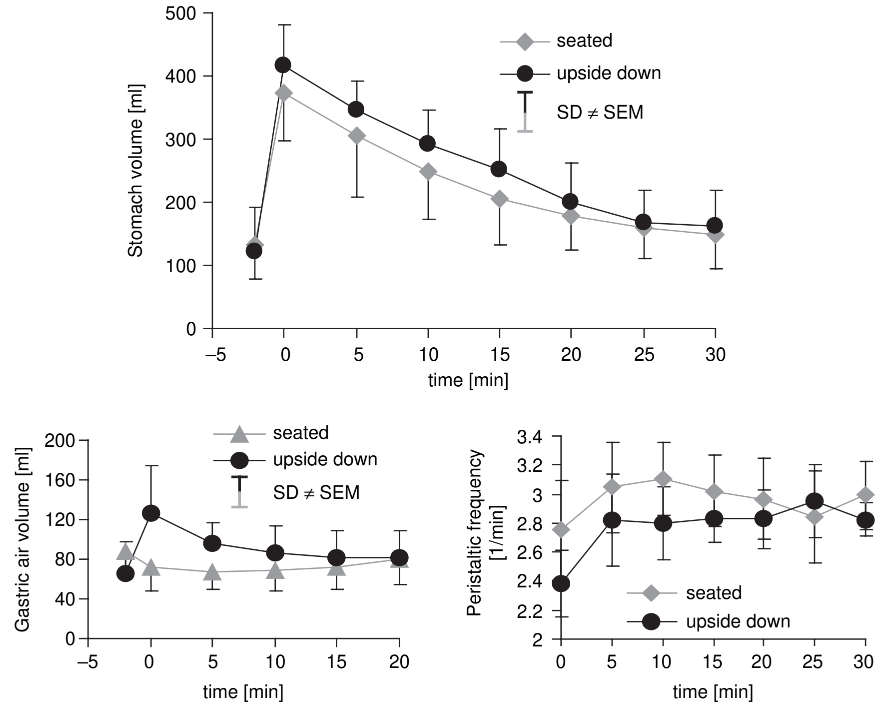

Figure 5. a. Total stomach volume in fasting state ($t = -2$ min) and over 30 min postprandial for seated position (SP) and upside-down position (UDP). Similar dynamics were observed for the stomach volume curves despite a difference in the emptying dynamics. b. Intragastric air in fasting state ($t = -2$ min) and during the first 20 min of gastric emptying (*left*). After the initial increase in gastric air volume in UDP, the air was continuously emptied into the small intestine within 15 min. Frequency curves, i.e. mean ($\pm$SD) contraction frequencies (1/min) over the 30 min study period in SP and UP (*right*). In both positions the contractile frequency increased over the first 5 min following meal ingestion, after which the frequency remained stable. Over the first 20 min, the contractile frequency in UDP was slightly lower than that in SP.

(similar characteristics of the frequency curves) during the first 20 min of the study period. No correlation was seen between peristaltic frequency and the rate of gastric emptying in either position.

Stomach and gastric air volume

On comparing the volume curves of the total stomach for SP and UDP, a significant effect of time (decrease in volume) (F_{stom} 2,25) $=155$, $p <$ 0.001), no effect of body position (similar volumes) and no interaction of body position and time (similar dynamics) were observed (Figure 5a). Gastric air volume was larger initially in UDP and emptied from the stomach within the first 15 min (in all but two volunteers). This is clearly reflected in the statistical analysis comparing the gastric air volumes curves for SP and UDP. The comparison over the first 20 min showed a significant effect of time ($F_{air}(2,20) = 4.5$, $p < 0.05$), a significant effect of body position ($F_{air}(1,11) = 6.6$, $p < 0.05$) and a significant interaction between body position and time ($F_{air}(2,23) = 6.1$, $p < 0.01$) (Figure 5b, left). Consequently, for UDP, there was a significant interaction between body position and time (different dynamics of volume curves) between the meal and stomach volume ($F_{UDP}(3,28) = 7.7$, $p = 0.001$). In SP, no common pattern for the change in air volume was observed and stomach volume curves showed similar characteristics.

Discussion

This study shows that posture has important effects on the physiology of gastric emptying for a non-nutrient liquid. The intragastric distribution of gastric contents was radically altered by moving from the upright, SP to the UDP. The distal stomach (antrum) was always filled with liquid in SP, whereas the proximal stomach (fundus) retained almost all the gastric content in UDP. Thus, in SP, passive forces (gravity and buoyancy) were conducive to the flow of liquid through the pylorus, whereas in UDP these factors acted against gastric emptying. Despite this fundamental change in the direction of forces, the rate of gastric emptying was similar in both positions.

In the fasting condition a difference in SP and UDP was observed only for gastric air volume. The smaller fasting air volume in UDP probably reflects compression due to the increased tension in the abdominal wall needed to maintain this strenuous position. After ingestion, initial meal volume was similar in both positions; however, the postprandial change in gastric volume (gastric relaxation) was greater in UDP mainly as a result of a significant increase in gastric air volume in this position. The larger volume response in UDP cannot be definitely explained by this study because intraluminal pressure measurements were not acquired. Nevertheless, the increase in initial postprandial gastric air volume in UDP may be due to either greater relaxation of the stomach or more retained air in the stomach (or both). That UDP is associated with greater gastric relaxation might be explained by the fact that fluid distends the fundus more effectively in this position, as if a larger meal had been ingested, triggering more profound receptive relaxation. In addition, the decrease in vagal stimulation known to occur in UDP would also decrease gastric tone and facilitate increased stomach volumes [26,27]. Conversely, the suppression of belching in UDP is conducive to the retention of gastric air, and although the use of a sports bottle minimized air swallowing, it cannot be excluded that this behavior was greater in UDP.

Changes in gastric peristalsis were also seen with position change. MRI motility scans revealed an initial increase in peristaltic frequency in both positions and a small reduction in peristaltic frequency in UDP compared to SP during gastric emptying. The initial increase in peristaltic frequency has also been observed following the ingestion of nutrient liquids [28], mixed solid/liquid meals [29] and a recent study that used manometry to detect antroduodenal contractions during barostat distension of the fundus [30]. Similar to the effects on stomach volume, the reduced frequency in UDP may be a consequence of greater gastric distension or increased vagal activity in this position. Together, these findings likely represent the initial regulation (adaptation) phase of gastric motor activity after a meal.

No correlation between gastric emptying and peristaltic frequency was found in SP or UDP. Furthermore, the change in peristaltic frequency did not explain the difference in gastric-emptying pattern between the two positions. The force of contraction cannot be assessed non-invasively; however, the occlusion of the distal stomach by propagating waves was similar in both positions. These findings suggest that peristalsis is not the primary force that drives gastric emptying, consistent with results of studies that have shown fluid emptying during periods of relative quiescence in antroduodenal peristaltic activity [10,12].

There was an important correlation between gastric emptying and the change in stomach volume after the meal (gastric relaxation) in SP. Gastric tone modulates intragastric pressure and thus the gastroduodenal pressure difference and the rate of gastric emptying [31]. In SP, the rate of gastric emptying was mainly determined by the hydrostatic pressure of the ingested liquid, a driving force that varies not only with gastric tone (i.e. change in volume and shape) but also with the volume ingested and the degree of gastric filling relative to gastric capacity [32]. The importance of the hydrostatic pressure in SP was further supported by the exponential dynamics of stomach and meal volume during emptying (constant air volume above the fluid level indicates that intragastric pressure remained constant). In theory, applying Torricelli's law [33], the change in liquid volume over time (V(t)) for hydrostatic pressure-driven emptying must follow the function: $V(t) = (a - bt)^2$, with time $t = [0, \frac{a}{b}]$, $a^2 =$ initial water volume ($V(0) \leq 300$ ml) and $b \leq \frac{\sqrt{V(0)}}{t_{empty}}$. This function closely resembles an exponential function ($V(t) = (ae^{-bt}$, $a = V(0)$, $b \leq \frac{\ln(2)}{t_{1/2}}$) for the given time period. Deviations from the exponential pattern expected if hydrostatic pressure drives gastric emptying to a more linear pattern can only be attributed to active changes in gastric contraction (i.e. peristaltic activity or gastric tone).

A linear gastric-emptying pattern was present in UDP, a position in which the effects of hydrostatic pressure operate against gastric emptying. Thus, this emptying pattern must have been produced mainly by active gastric contraction (see rationale above). As presented in Figure 5a, stomach volume decreased continuously over time (especially the proximal volume) because of continuous adaptation in gastric tone, which provided a constant delivery of water into the distal antrum, through the pylorus and into the duodenum. The presence of a positive gastroduodenal pressure gradient is evidenced by the finding that gastric air also emptied continuously (and rapidly) from the stomach into the small bowel (Figure 5b). Although gastric-emptying time was not associated with peristaltic frequency, the driving force provided by peristaltic contraction waves was not assessed and it cannot be excluded that these contributed to gastric emptying. If present, this process may be of particular importance in UDP, aiding the distal transport of gastric contents against the effects of gravity. Ultimately, the precise role of gastric peristalsis in gastric emptying awaits advances in gastric MRI that allow concurrent (rather than alternating) recording and analysis of gastric volume and motility scans.

For the purposes of this study a non-nutrient liquid, water, was preferred to a nutrient liquid meal to keep the duration of the study to a minimum (given the strenuous upside-down position) and to avoid potential confounding by modulation of gastric emptying by intestinal chemoreceptors. Nevertheless, enteral feedback inhibition may also have an effect on the rate of water gastric emptying. In SP, with the duodenum in a dependent position, increased pyloric resistance mediated by duodenal mechanoreceptors stimulated by duodenal distension may inhibit rapid water emptying [34]. In UDP, this control mechanism was probably not active. The non-invasive study design precluded the use of concurrent intraluminal antropyloroduodenal manometry recordings required to investigate this possibility.

The insights into gastric physiology provided by this study are the result of developments in gastric MRI. This technology provides a comprehensive description of gastric function by simultaneously detecting gastric emptying and gastric tonic and peristaltic motor function, and uniquely the assessment of intragastric distribution of gastric contents. This study demonstrates vividly the value of MRI as a non-invasive investigation of gastrointestinal structure and function.

In conclusion, the stomach maintains the rate of gastric emptying for a non-nutrient fluid despite radical changes in body position and intragastric distribution of gastric contents. In SP, the exponential gastric-emptying pattern indicates the importance of hydrostatic pressure to the emptying process (modulated by gastric tone). In UDP, where hydrostatic pressure acts against gastric emptying, the linear gastric-emptying pattern is also likely to be mediated by a continuous adaptation of gastric tone maintaining a constant gastroduodenal pressure gradient. These findings provide further support for the hypothesis that the stomach resembles a "pressure pump" rather than a "peristaltic pump".

Acknowledgements

The study was supported by the Swiss National Science Foundation (SNF grants 32–54056.98 and 31–55932.98).

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